J-PARC Japan Proton Accelerator Research Complex Accelerator

Simulation of resonances and beam loss for the J-PARC Main Ring

Alexander Molodozhentsev (KEK)

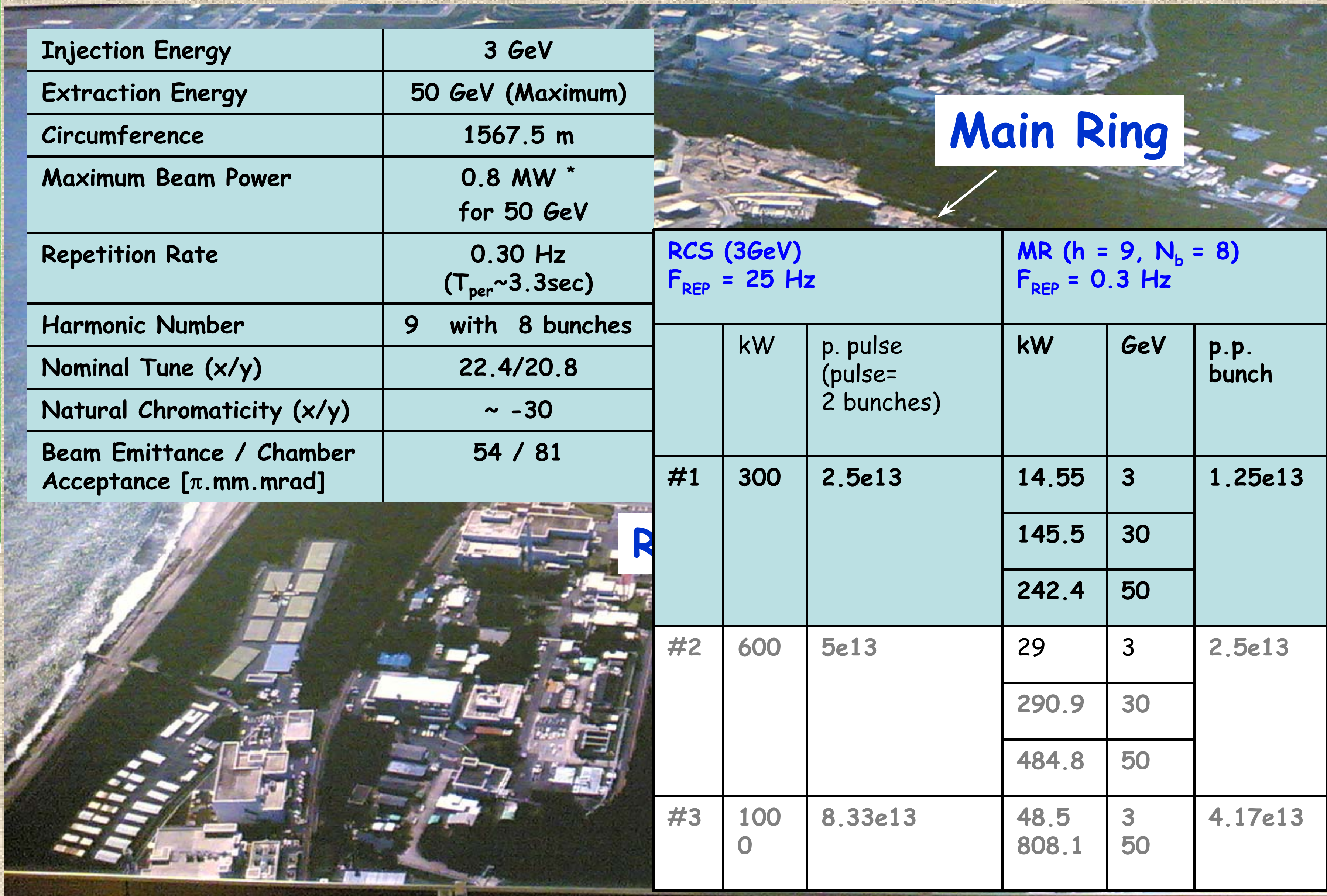
Etienne Forest (KEK)

for the ICFA HB08 Workshop

Contents of the talk:

- Main Ring design performance
- Lattice design and MR imperfections
- Detuning effects and resonances
- Simulation tools … PTC_ORBIT
- Single and multi-particle dynamics
  - Optimization of MR performance
  - Space charge effects including the realistic machine imperfections
  - Coherent mode analysis
- 'Sum' linear coupling resonance:
  - Observation & Correction
- Beam-loss budget for MR operation
- Conclusions

JPARC Main Ring design performance



Injection Energy	3 GeV
Extraction Energy	50 GeV (Maximum)
Circumference	1567.5 m
Maximum Beam Power	0.8 MW * for 50 GeV
Repetition Rate	0.30 Hz (T_{per}~3.3sec)
Harmonic Number	9 with 8 bunches
Nominal Tune (x/y)	22.4/20.8
Natural Chromaticity (x/y)	~ -30
Beam Emittance / Chamber Acceptance [π.mm.mrad]	54 / 81

RCS (3GeV) F_{REP} = 25 Hz			MR (h = 9, N_b = 8) F_{REP} = 0.3 Hz		
	kW	p. pulse (pulse= 2 bunches)	kW	GeV	p.p. bunch
#1	300	2.5e13	14.55	3	1.25e13
			145.5	30	
			242.4	50	
#2	600	5e13	29	3	2.5e13
			290.9	30	
			484.8	50	
#3	100 0	8.33e13	48.5 808.1	3 50	4.17e13

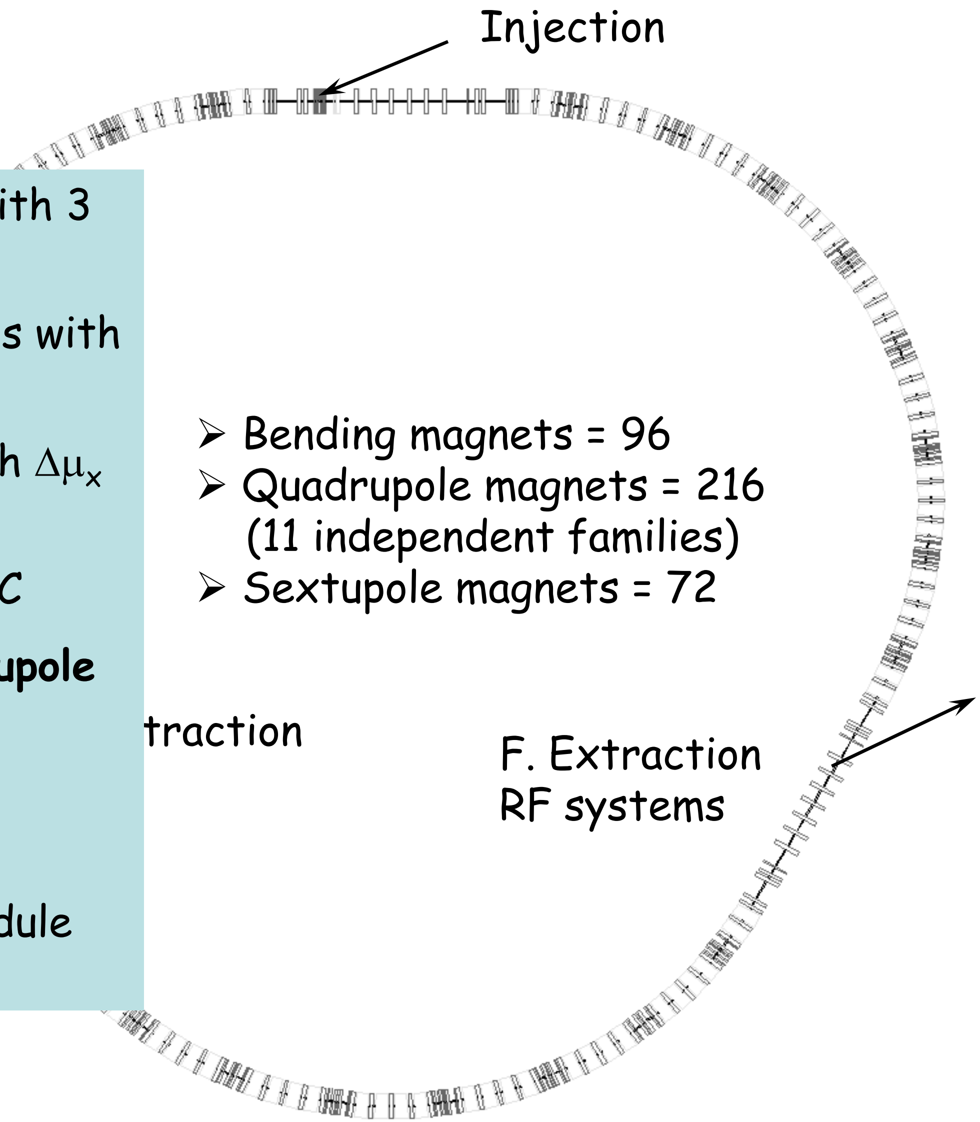
Main Ring lattice design

- 'imaginary' transition lattice with 3 super-periods;
- ARC is based on the FODO cells with the 'missing' bend
- ARC consists of 8 modules with $\Delta\mu_x \sim 3\pi/2$ per module …

(1) **zero dispersion** outside of ARC

(2) provide **cancellation the sextupole nonlinearity**

- 'slow' extraction by using $3Q_x$ resonance
- Vertical phase advance per module can be varied from π to $3\pi/2$.



- Bending magnets = 96
- Quadrupole magnets = 216 (11 independent families)
- Sextupole magnets = 72

Main Ring imperfections (1)

Measured data

❖ **Error of the dipole field of the MR Bending magnets** at the injection energy … $\{(\Delta BL)/\Delta BL\}$:: $1\sigma = 2.4\times10^{-4}$, cut = 2σ

❖ **Error of Quadrupole strength of MR Quadrupole magnets** at the injection energy …
$\{\Delta B'L/(B'L)\}_k$ :: $1\sigma = 3.26703\times10^{-4}$, cut = 4σ … **PLUS:** k5L components

❖ **Error of Sextupole component of MR Sextupole magnets** at the injection energy …
average relative deviation from the required values is
$|\delta b_3| < 0.002$ … **PLUS:** k8L components

❖ **Sextupole component of MR Bending magnets** at the injection energy…
$\langle k2L\rangle_{MAD} \sim$ $\mathbf{5.2\times10^{-3}}$ $[m^{-2}]$ :: $1\sigma = 4.2\times10^{-3}$ $[m^{-2}]$, cut=3σ.

Location of each magnet is fixed around MR after the shuffling procedure to minimize [EPAC06] :

- **COD**
- **beta-beating**
- **$3Q_x$ resonance driving terms**

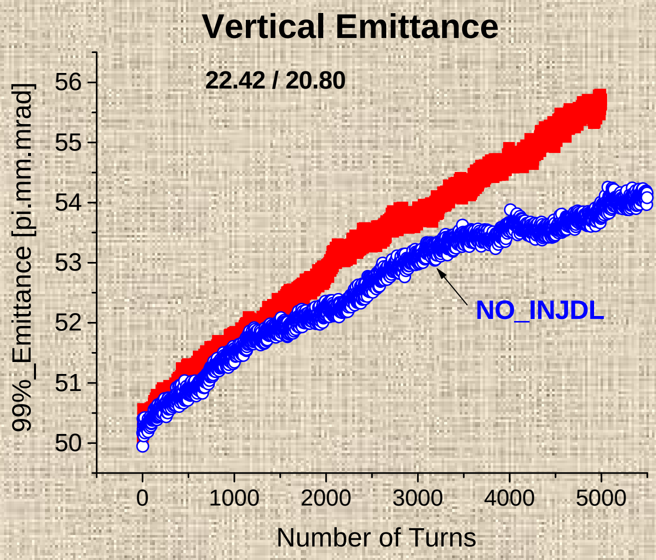
Main Ring imperfections (2)

- **Injection 'dog-leg'**, created by 3 Bump Magnets … like DC magnets during the injection procedure.

- **Field leakage** of the injection septum magnet (measured data), which contains mainly quadrupole and sextupole field components.

  - **Edge focusing effect** of the Bump magnets will lead to the vertical beta-beating < 5%.

  - Distortion of the 'super periodicity' will **lead the transverse emittance dilution, caused by 'non-structure' resonances**, like [1,2,64], [3,0,67] and [0,4,83], in **addition to the 'structure'** resonances: [4,0,90], [2,-2,3].



- **Alignment errors of the MR magnets**:

{QM}$_{TILT}$: Gaussian / 1σ=0.2mrad / cut=2σ
{SM}$_{SHIFT}$: G: 1σ=0.3…0.5mm / cut=2σ
{SM}$_{TILT}$: Gaussian / 1σ=0.2mrad / cut=2σ

Beam Power: 1.8kW/bunch
Bunching factor ~ 0.2
Full chromaticity correction

Main Ring basic operation scenario

- ❖ MR operation scenario is based on the RF system working on the fundamental harmonic h=9 … **8 bunches** should be accumulated in MR during the injection process.
- ❖ RCS (F_{REP}=25Hz, h=2) should provide MR by batch per pulse, containing **2 bunches** with the beam power of **1.8kW/bunch** (3GeV)

➢ Minimum injection time for MR is <u>about 125 msec</u> … ~ 22'000 turns.

- ❖ Acceleration process is based on the constant RF voltage (**210kV**).
- ❖ Longitudinal emittance at the injection energy should be about **3eV.sec**
- ❖ Transverse emittance of the beam, injected from RCS, depends on the acceptance of the collimator of the RCS-MR beam-line (54π).
- ❖ MR collimation system has variable physical acceptance **54÷81**π.
- ❖ Design capacity of the MR collimation system is **<u>450Watt</u>**.

➢ <u>Keep the particle losses below this limit.</u>

Milestones for MR optimization

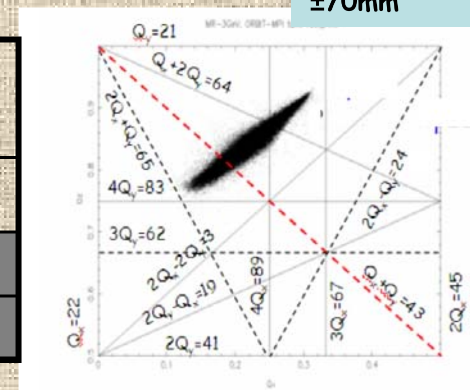
- Minimize the influence of the structure resonances … avoid these resonances if it's possible.
- Keep the bunching factor as big as possible for the given longitudinal emittance, providing the matched condition to avoid fluctuation of the bunching factor during the injection process and at the beginning of the acceleration process.
- Minimize the transverse mismatching at the injection point.
- Identify of the most dangerous resonances for the MR operation and apply the appropriate correction scheme.
- Minimize the budget of the lost beam power for the MR operation by using available knobs (different physical acceptance of the collimation systems of the RCS_MR beam-line and MR).

Space charge detuning and resonances

Detuning budget at the injection energy (1.8kW/bunch)

Chromatic detuning ($\Delta p/p=\pm0.004$)	±0.12 (before CC) ~ 0 (after CC)
Amplitude dependent detuning ($\varepsilon=54\pi$)	~ +0.02 (after CC)
Incoherent space charge detuning	~ -0.17 ($B_f=0.16$)
Coherent space charge detuning (H/V)	~ -0.04/-0.07

Rectangular chamber: ±70mm



Resonance	Harmonic number	Type of resonance	Source of resonance *	Status
[2,0]	45	Normal 'quadrupole'	Q-error & misalignment	√
[3,0] [1,2], [-1,2]	67 64 19	Normal 'sextupole'	Sextupole field comp. in BM + Sextupole errors + FF_BM	√ √
[4,0],[2,-2], [2,2], [0,4]	90, 3 86, 83	Normal 'octupole'	Space charge Sextupole Field FF_QM	√ √
[1,-1]	*43*	*Skew 'quadrupole'*	*Q magnet tilt* *SX magnet shift*	√ √
[0,3], [2,1], *[2,-1]*	*62, 65,* *24*	*Skew 'sextupole'*	*Magnet errors* *SX magnet tilt*	√ √

Beam

RCS:: **300kW** // 3BT collimator:: **54**π jaw (Losses:135W@14.5kW)

MR beam power at 3 GeV:: 14.5kW (for 8 bunches) :: 1.8kW/bunch :: 1.25e13 ppb

Transverse distribution -> based on the RCS 3GeV distribution ('realistic' distribution).

Longitudinal distribution -> generated (parabolic) with ε_L ~ 3eV.sec :: B_f = 0.16 (V_{RF}=210kV,h=9)

Matched or Mismatched particle distribution (Tr&L)

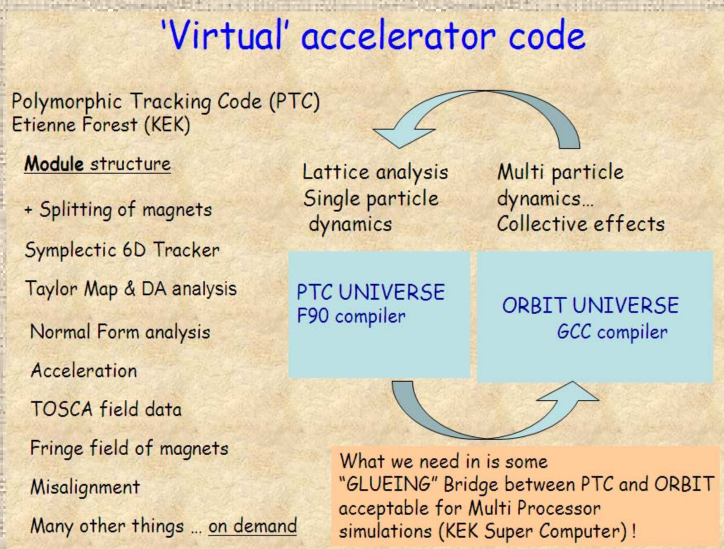
Simulation tools … PTC_ORBIT

Idea had been discussed during the HB06 workshop:

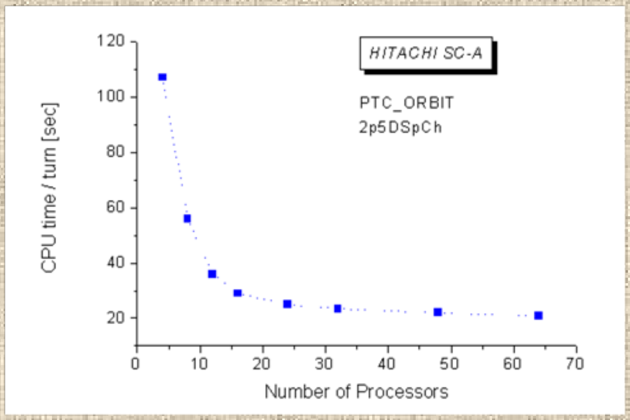
…when the 'magnet splitting' procedure has been developed for the PTC code, it opened possibilities to put any kind of collective nodes in any place of the PTC magnet system.

In frame of this combination the PTC code provides the symplectic propagator between the 'ORBIT' space charge nodes, distributed around the ring at some locations…
PLUS: normal form analysis, acceleration, misalignment, fringe fields.

KEK_SNS collaboration effort



The PTC_ORBIT code



KEK super-computer system

Choice of model and main parameters

To study the space charge effects for MR we adopted the simplified model (the "2+1/2D" model), implemented to the 'ORBIT' code. For this model the transverse space charge fields are determined by using the 2D Poisson solver with fixed size of the boundary. Coupling the longitudinal motion into the transverse tune space is determined by scaling the space-charge force on the given macro-particle according to the longitudinal charge density at its position in the bunch.

The transverse space charge forces are evaluated as nonlinear kicks using the explicit second order PIC model and FFT.

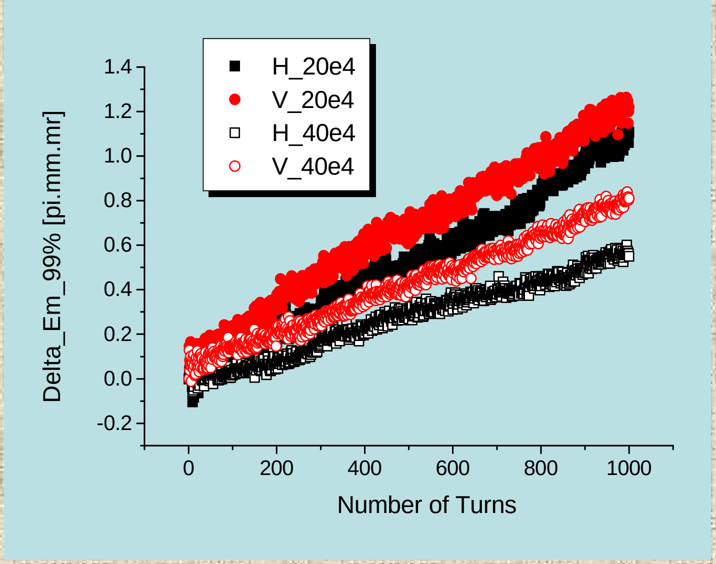
Convergence study:

- the number of the azimuthal integration steps;
- the number of macro-particles;
- the spatial resolution, the grid parameter

for the FFT algorithm.

N_{az} = 256 (128)
N_{mp} ~ 200e3
N_{FFT} = 128×128 … ~ 50mp/mesh
N_{SC_NODE} ~ 1000

CPU_time/turn (16p_HitachiSC) ≥ 10 sec



Optimization of MR performance

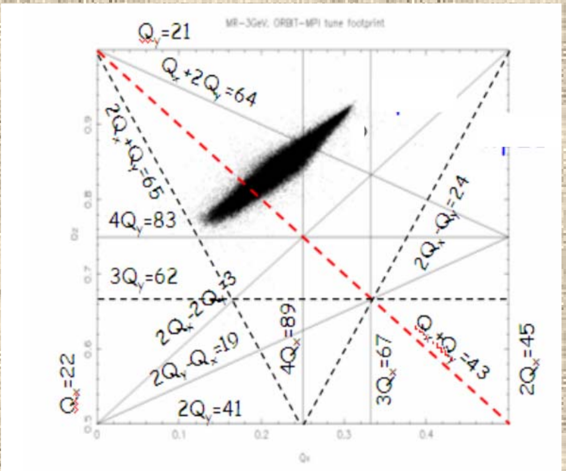
Tune scanning for the moderate beam power

Bad (red) | Good (yellow) | **Relative values** ... (to the best)

	Q_y \ Q_x	22.118	22.168	22.218	22.268	22.318	22.368	22.418	22.468
	20.914					1.165			
1	20.87	1.477	2.815	3.685	1.158	1	1.593	1.111	1.147
2	20.82	1.192	1.511	2.709	3.39	1.86	1.001	1.294	1.081
3	20.78	1.31	1.405	1.671	3.653	3.444	1.196	1.084	1.057
4	20.73	1.299	1.349	2.102	1.882	3.148	3.701	1.743	1.211
5	20.68	1.486	1.653	1.778	1.577	2.129	3.742	3.83	1.707
		8	7	6	5	4	3	2	1

$Q_x+Q_y=43$

$2Q_x-2Q_y=3$



- ✓ Matched 6D distribution at the injection point for each tune
- ✓ Observation during 4000 turns
- ✓ MR scraper acceptance is 60π
- ✓ Bunching factor is 0.16 for V_{RF}=210kV

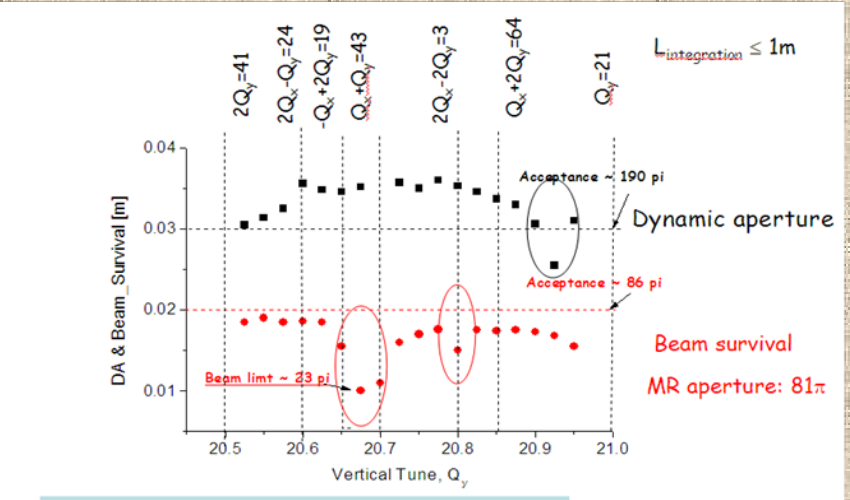
The 'basic' bare working point for the moderate beam power
has been chosen with the following betatron tunes: **Q_x=22.318, Q_y=20.87**

Analysis of single particle dynamics (PTC)

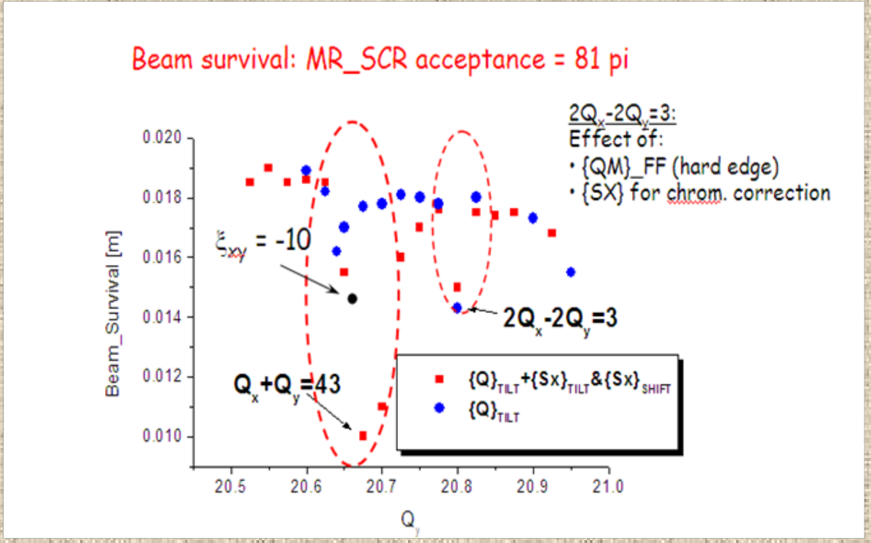
Dynamic aperture (DA) and **Beam survival** at the MR collimator

Nonlinearities & errors:

- ❑ sextupole magnets for the chromaticity correction
- ❑ fringe-field of the quadrupole magnets
- ❑ strength error of the quadrupole magnets (systematic)
- ❑ strength error of the sextupole magnets (systematic)
- ❑ misalignment errors (random 'linear coupling' errors):
  - ➢ tilt of quadrupole magnets
  - ➢ H/V shift of sextupole magnets
  - ➢ tilt of sextupole magnets

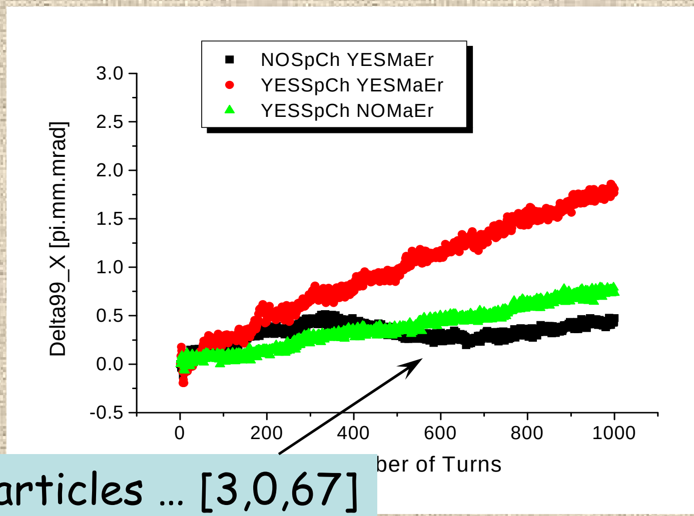


Q_x = 22.30 (fixed) / 'Full' chromaticity correction

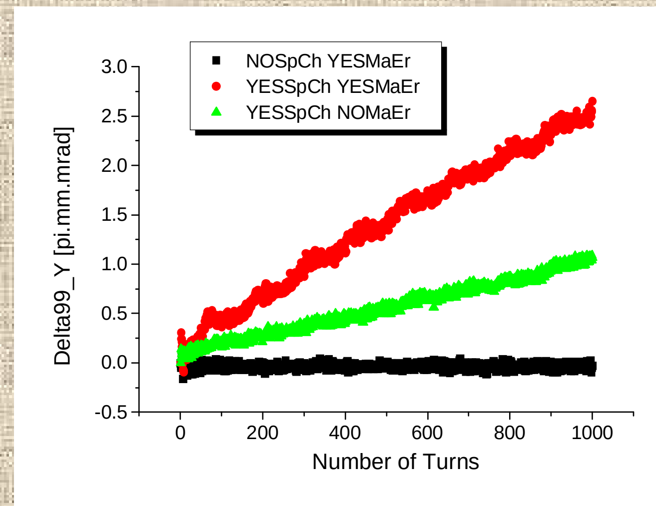


Combined effects of the space charge and misalignment errors

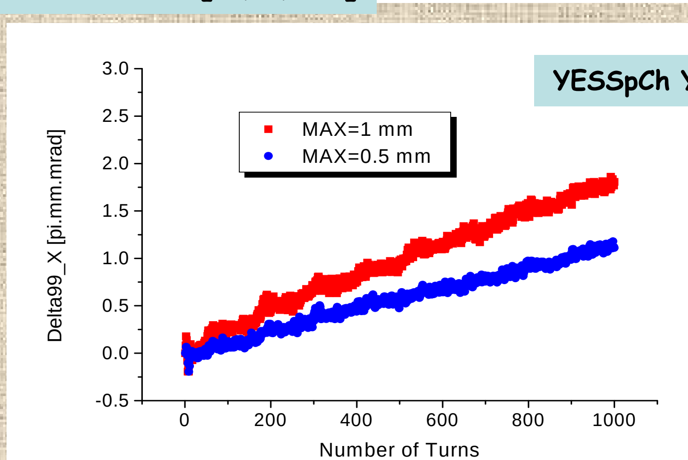
… for the 'basic' bare working point Qx=22.318, Qy=20.87

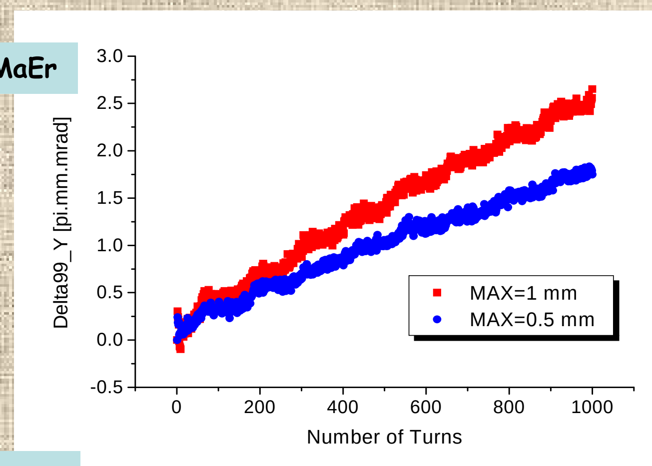


Tail particles … [3,0,67]



YESSpCh YESMaEr



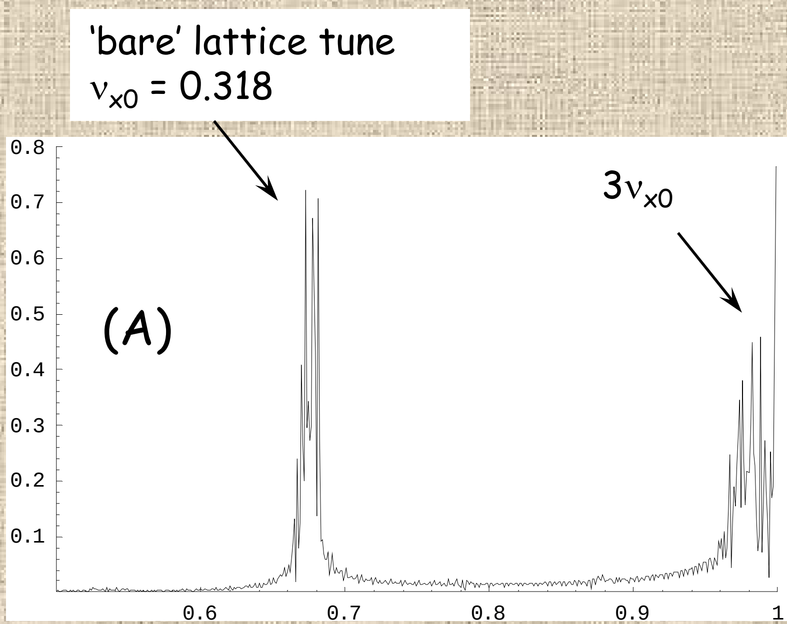


… effect of the sextupole misalignment errors

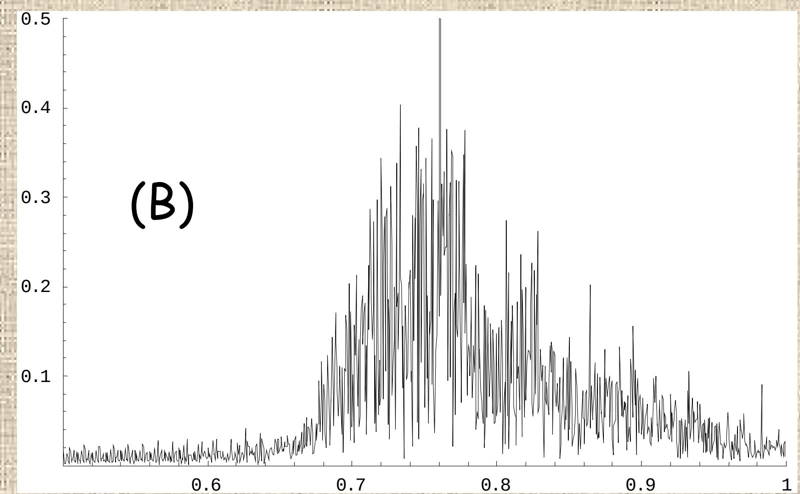
J-PARC Japan Proton Accelerator Research Complex Accelerator

Coherent mode analysis (1)

DFT of the **<X³> moment** of the evolution of the transverse particle distribution during 1000 turns … the [3,0,67] resonance.



Detuning effect of the low energy space charge

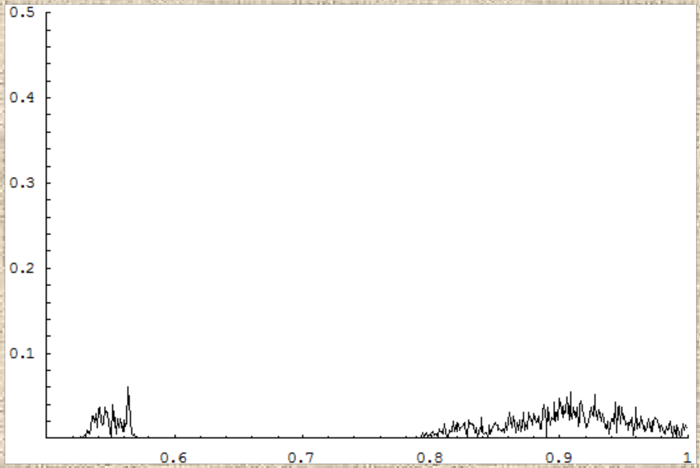


Spectrum analysis of the **<X3> coherent mode** for the 'basic working point **without** (A) and **with** (B) **the space charge detuning effect**.

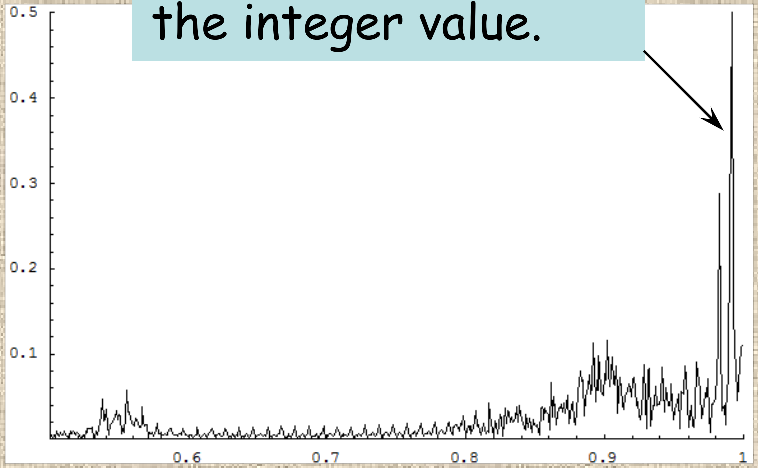
Coherent mode analysis (2)

DFT of the **<XY> moment** of the evolution of the transverse particle distribution during 1000 turns … the linear coupling resonance [1,1,43].

NO linear coupling resonance



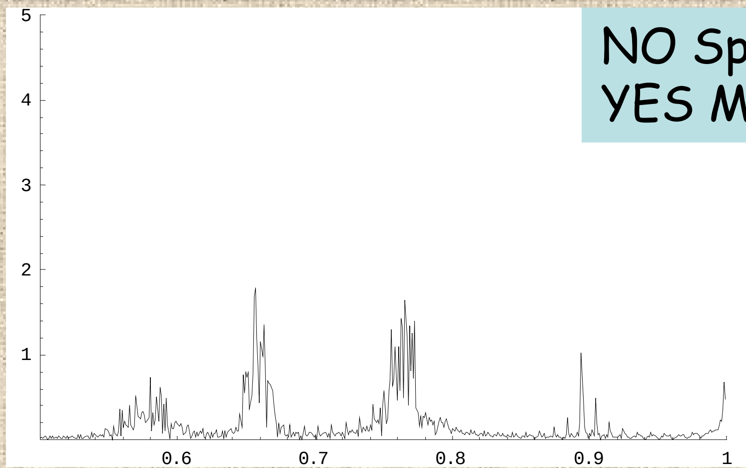
Sign of the linear coupling resonance … coherent tune near the integer value.



Spectrum analysis of the **<XY> coherent mode** for the 'basic working point including the low energy space charge effects **without** (A) and **with** (B) the **LC alignment errors.**

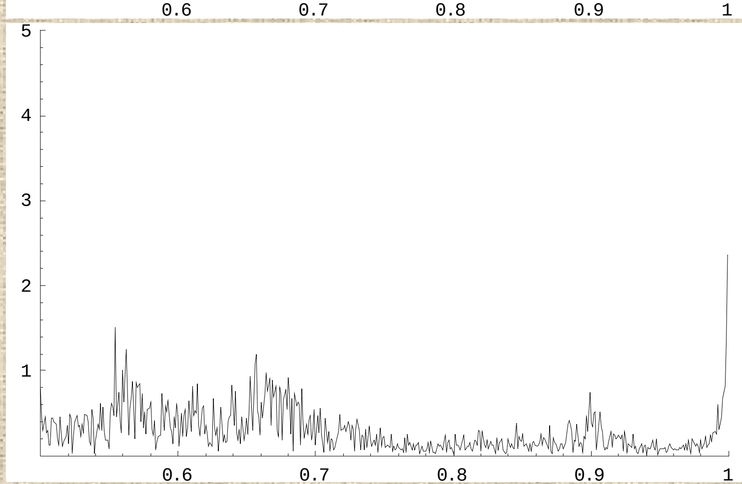
Coherent mode analysis (3)

High order coupling: $\langle X^2Y^2 \rangle$ … similar effects for $\langle X^4 \rangle$, $\langle Y^4 \rangle$

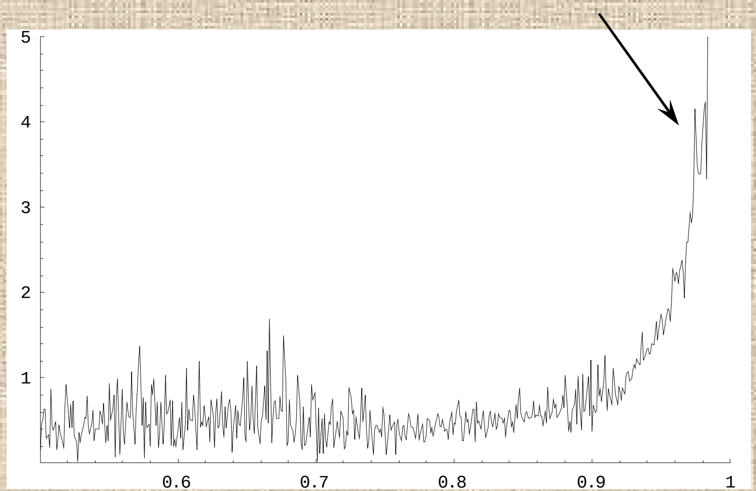


NO Space Charge
YES MisAlERR

Strong high-order coupling



YES Space Charge
NO MisAlERR



YES Space Charge
YES MisAlERR

Conclusions from coherent mode analysis:

… for the 'basic' bare working point Qx=22.318, Qy=20.87

- In the case of misalignment errors and 'zero' beam power the dilution of the transverse emittance is caused by the [3,0,67] resonance, but the effect is quite small and can not lead to the particle losses during the injection process.

NO linear coupling resonance for the 'zero' beam power.

- The space charge of the beam with the moderate beam power without any misalignment errors leads to:
  - detuning effect … NO sign of the [3,0,67] resonance;
  - excitation of the $4Q_x$, $4Q_y$, $2Q_x \pm 2Q_y$ resonances in addition to $2Q_x$ and $2Q_y$.
  - NO 'linear' coupling resonance.

- In the case of the moderate beam power and the misalignment errors the main source for the particle losses is the 'sum' linear coupling resonance.
- In addition, influence of the 'space-charge' resonances becomes quite significant.

Correction the linear coupling resonance [1,1,43]

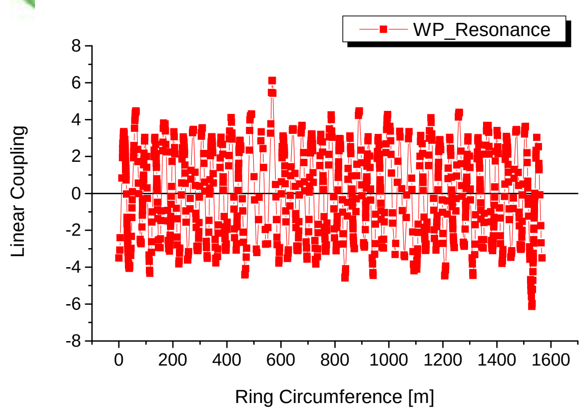
By using this set of the skew-quadrupole magnets one can make a 'global' or a 'local' correction of the linear coupling resonance driving term.

The 'global' correction of the linear coupling resonance allows minimize the remained coupling after the correction around the whole ring.

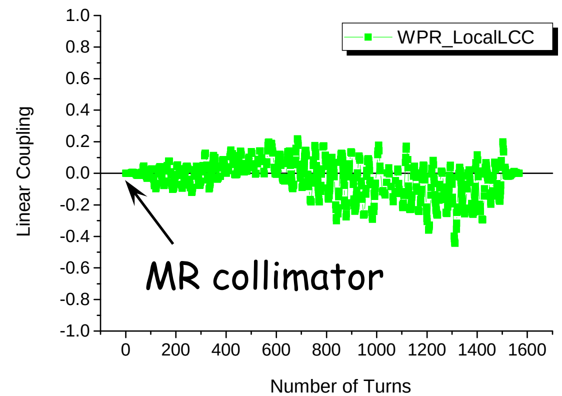
In the case of the 'local' correction of the linear coupling resonance, the linear decoupling has been performed at the location of the MR collimation system.

The correction procedure has been implemented to the 'PTC' code for the both decoupling algorithms: the 'local' and 'global' decoupling.

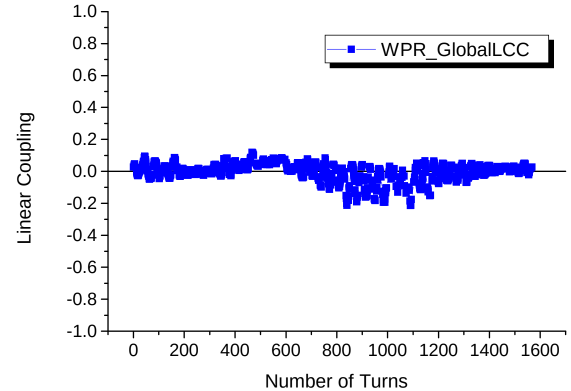
Coupling parameter: d<XY>/dI_1



WPR:: Q_x =22.21 / Q_y =20.80



'Local' decoupling



'Global' decoupling

'Linear_Decoupling' algorithms in PTC

Local Matrix Decoupling

The local method is a simple matrix decoupling at the point of observation (at the position of the MR collimator). If the one-turn matrix at the collimator is given by *M*, then we simply use several families of skew-quadrupole magnets to uncouple the lattice.

Using the "Fully Polymorphic Package" of PTC we compute: $M_{ij} = M_{ij}^0 + \sum_n^{N_p} \frac{dM_{ij}}{dk_n} \Delta k_n$

Using a Newton search, which minimizes $\sum_{n=1}^{N_p} \Delta k_n^2$, we solve the equations $M_{ij} = 0$

Global reduction of Linear Coupling

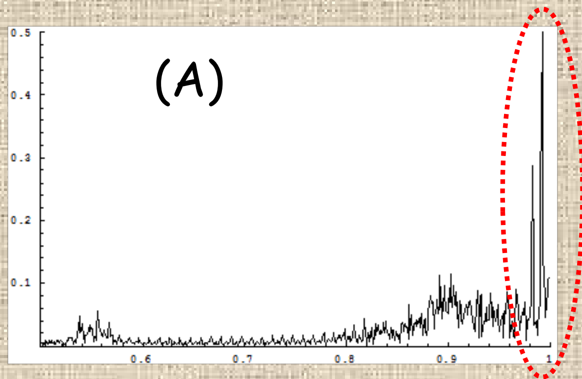
The global reduction of the Linear Coupling can be made by minimizing a 'Ripken' lattice function summed around the ring. We can define this function denoted at any point around the lattice: $< y^2 > \; = \; \beta_{yy} < I_y > + \beta_{yx} < I_x >$

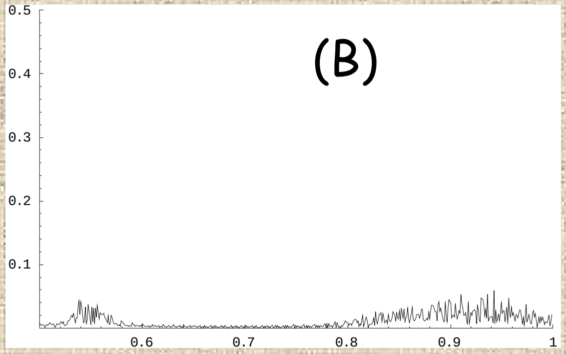
We then sum this lattice function around the ring: $F = \oint_C \beta_{yx}(s) ds$

Again, using a Newton search, we solve for: $\frac{dF}{dk_n} = \oint_C \frac{d\beta_{yx}(s)}{dk_n} ds = \sum_{i=magnets} \frac{d\beta_{yx}(i)}{dk_n} L_i$

to find the minimum of the function *F* for some setting of the skew-quadrupole magnets.

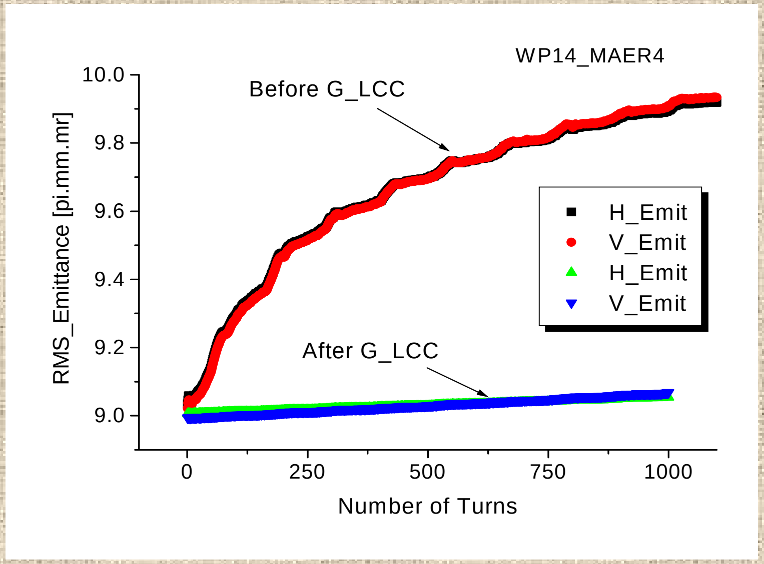
'Global' linear decoupling and space charge effects for MR



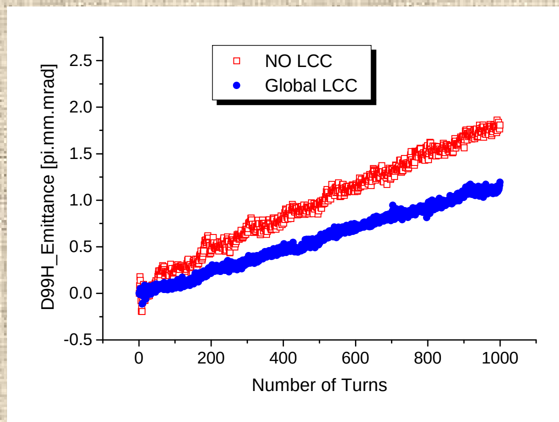


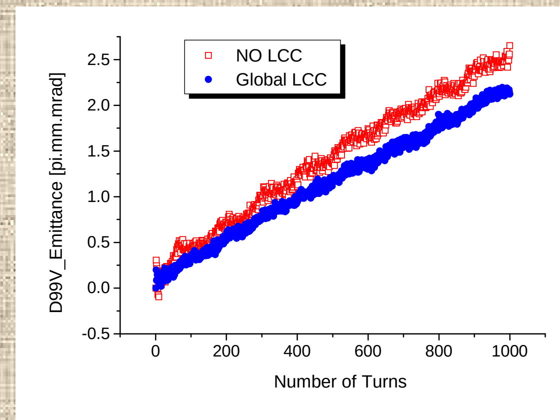
Spectrum analysis of the **<XY> coherent mode** for the 'basic working point including the low energy space charge effects **before** (A) and **after** (B) the LC 'global' correction.

RMS emittance (H&V) before and after the 'global' linear coupling correction for the 'basic' bare working point.

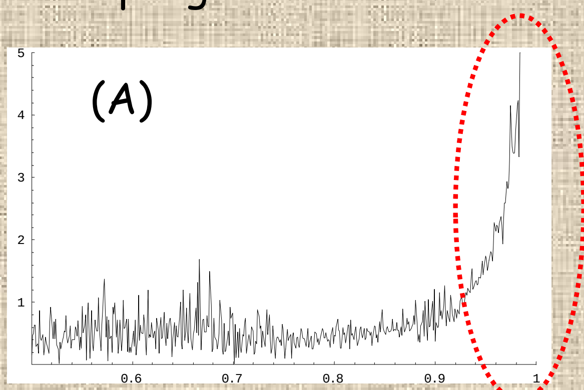


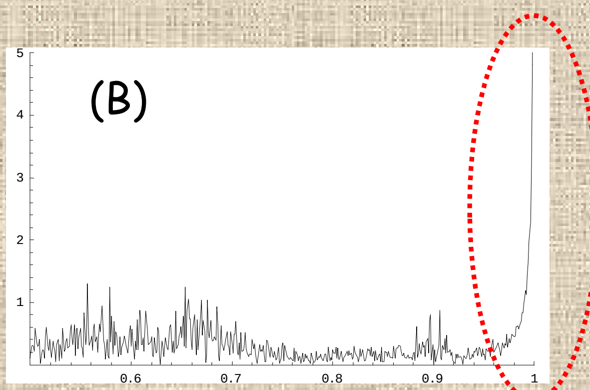
Remained effects after the linear decoupling …





…the remained effects of the 4th order coherent resonances lead to the transverse emittance growth for both transverse phase planes after the linear coupling correction.





Spectrum analysis of the $\langle X^2Y^2 \rangle$ coherent mode for the 'basic' working point before (A) and after (B) the global linear coupling correction.
… similar results for $\langle X^4 \rangle$ and $\langle Y^4 \rangle$ have been obtained.

Beam-loss budget estimation for the moderate beam power (1)

Beam-loss budget has been established for the MR basic operation scenario for the moderate beam power:

- V_{RF}=210kV (h=9, fundamental harmonic)
- B_f = 0.16 with the longitudinal emittance of 3eV.sec
- beam power 1.8kW/bunch (3GeV) … 8 bunches operation
- RCS(3GeV):: 300kW … realistic TR_6D distribution
- RCS_MR beam line collimator: 54π mm.mr → Losses::135W@14.5kW(3GeV)
- 'Basic' working point: Q_x =22.318, Q_y =20.870
- MR field imperfections, based on the field measurements for all magnets
- Location of the magnets … after the 'shuffling' procedure
- Misalignment errors of the quadrupole and sextupole magnets

Different conditions:

- Transverse matched and mismatched distribution (10% beta mismatching)
- Acceptance of the MR collimation system: 60π or 65π
- Axial shift of the MR sextupole magnets: (maximum) 1mm or 0.6mm.

Beam-loss budget estimation for the moderate beam power (2)

"Bare" working point: Q_x =22.318, Q_y =20.870 1.8kW/bunch@3GeV

Injection process

		B_f = 0.16 (V_{RF} = 210kV)	
		MRSCR=60π	MRSCR=65π
Max V_shift {SM} = 1mm	NO_LCC	190×2 125×2 60×2 5×2 Total: ~ 760W TmM (~ 1.1kW)	~ 40% from 60π Total: ~ 310W TmM (~ 465W)
	GLCC: 4skewQM	125×2 80×2 40×2 2×2 Total: ~500W TmM (~ 750W)	~ 50% from 60π Total: ~ 250W TmM (~ 375W)
Max V_shift {SM} = 0.6mm	NO_LCC	Total: ~ 142W TmM (~ 240W)	NO DATA

Acceleration process:

Losses: (MRSCR=60π) ~ 12W/bunch … ~ **100W** (8unches).

Conclusions (1):

- PTC_ORBIT code has been developed as the tool for the comprehensive analysis of the single particle dynamics and the space charge effects in space charge dominated synchrotrons. The combined code with all required libraries has been compiled for the multi-processors super computer of KEK.

- Optimization of the performance of J-PARC Main Ring has been performed for the moderate beam power of 1.8kW/bunch at the injection energy of 3GeV including the tune-scanning, resonance study, correction of the linear coupling resonance.

- Realistic machine imperfections including the measured field components of the MR magnets, the field leakage of the injection septum, magnet alignment errors have been used to the performed study. The initial particle distribution for the MR study has been obtained after the RCS study including the injection and acceleration process for the beam power of 300kW at 3GeV.

Conclusions (2):

- The 'sum' linear coupling resonance [1,1,43] has been recognized as the most dangerous low-order resonance for the operation with the moderate MR beam power, which leads to significant particle losses during the injection process. The main source of this resonance for the MR operation is the vertical closed orbit distortion at the location of the sextupole magnets and the alignment error of the MR sextupole magnets.

- The correction scheme to make the local or global linear decoupling for the MR operation has been applied successfully. The correction scheme is based on four independent skew quadrupole magnets placed at the dispersion free straight sections.

- The transverse emittance growth, observed after the linear coupling correction, caused by high-order resonances $4Q_x$, $4Q_y$ and $2Q_x+2Q_y$ for the basic 'bare' working point Q_x=22.318 and Q_y=20.870. This effect can be minimized by making the local correction of the vertical cod at the location of the MR sextupole magnets.

- The beam loss budget has been established for the basic operation scenario in the case of the moderate beam power including the acceleration process.

Thanks for attention.